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CHARACTERIZATION OF HIGH POWER GAS SWITCH FAILURE MECHANISMS

E. E. NOLTING

Naval Surface Weapons Center
White Oak, Silver Spring, Maryland 20910

Abstract

A multistage, 4 MV, low jitter, command triggered gas switch is being developed for use on large pulse power devices. Experiments to date have shown that the performance and operational life of the switch are severely limited by mechanical and electrical failure of the insulating housing. Estimates of the internal overpressure produced during switch closure have been made which indicate the severity of the blast containment problem; this information has led to the development of a mechanically stronger switch design. Surface analyses performed on both switch electrode and insulator surfaces were used to investigate observed electrical failure of the insulators. A layer of closely spaced metal particles were found imbedded in the insulator walls.

Introduction

During the past year and a half the Naval Surface Weapons Center, White Oak Laboratory (NSWC/WOL), and Pulsar Associates, Inc. (PAI)*, have cooperated on the development of a 4 MV, low jitter, command triggered, gas switch. The fully developed switch is intended for use on high power, single pulse devices and testing has been performed on the Defense Nuclear Agency's Casino nuclear weapons effects simulator. At present the Casino simulator has four three-electrode water switches which each transfer a nominal 100 kJ from four 2.5Ω pulse-forming lines into matched loads. The gas switches, when fully operational, will be used to replace the water switches.

There are several reasons why operable gas switches would be preferable to the existing water switches. First, recent computer studies of switch parameters indicate that water switches are inherently more resistive and suffer from time dependent capacitive coupling effects.[1] Therefore, water switches have a substantially greater loss in delivered power and energy than those with a gas dielectric. Second, gas switches can be operated with less jitter, an important consideration when synchronization is required. Third, the mechanical shock associated with switch closure is considerably less with a gas dielectric switch. Reduction of mechanical shock lengthens both switch and machine lifetimes. Fourth, current distribution in gas switches is more controllable than in water switches; therefore, switch inductance and resistance exhibit less shot-to-shot variation.

The design goals for the gas switch development are: (1) a maximum hold off voltage of 4 MV with a pulseline charge time of 1.5 μsec, (2) a transfer of .05 coulomb and 100 kJ in a single pulse, and (3) a command trigger with a maximum jitter of less than 10 ns. Presently there are no switches which meet all of these requirements.[2,3]

Description of Switch

Figure 1 illustrates the design of a single section of the multistage switch tested at Casino. Switch voltage is equally divided across each stage (within five percent),[4] an arrangement that gives the maximum voltage hold off for the multistage switch configuration for a fixed gas pressure. Several gas dielectrics have been tried. An equal part mixture of sulfur hexafluoride and argon has been found to give most satisfactory results in terms of dielectric strength and cleanliness.

Various triggering schemes have been employed to command fire the gas switches; however, all the methods have used the same fundamental design. A high voltage signal is input at the positive end of the switch producing ultraviolet illumination of the negative electrode. The illuminated electrode emits electrons which initiate rapid closure of the triggered stage. An annular electrode configuration allows the ultraviolet radiation produced by the closure of the triggered gap to radiate the second stage. Each succeeding stage is illuminated by the preceding gap in the same manner until the entire switch is closed.

The entire switch column assembly was rigidly connected at the positive (output) end of the switch. At the opposite end, the switch columns were attached to a plate which was electrically connected by several short, braided straps. This cantilevered switch assembly allowed shifting of the pulseline and transformer, when transmission line fluids were transferred, without creating stresses in the switch components. Figure 2 shows location and mounting of the switch assembly.

Illuminated, multistage switches of similar design have demonstrated low jitter operation.[5] The maximum voltage the switch is able to sustain is determined by switch length, i.e., the number

*Pulsar Associates, Inc.
11491 Sorrento Valley Road
San Diego, California 92121

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14. ABSTRACT
A multistage, 4 MV, low jitter, command triggered gas switch is being developed for use on large pulse power devices. Experiments to date have shown that the performance and operational life of the switch are severely limited by mechanical and electrical failure of the insulating housing. Estimates of the internal overpressure produced during switch closure have been made which indicate the severity of the blast containment problem; this information has led to the development of a mechanically stronger switch design. Surface analyses performed on both switch electrode and insulator surfaces were used to investigate observed electrical failure of the insulators. A layer of closely spaced metal particles were found imbedded in the insulator walls.

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of stages employed.

Discussion of Mechanical Failure in Gas Switch

The first gas switch tested at Casino had 2.5 cm diameter brass electrodes and an acrylic insulator 2.4 cm in length and 5 cm in diameter. The entire switch assembly consisted of six parallel columns, each with 18 stages, evenly spaced on a 25 cm diameter bolt circle. This configuration provided about 5 ns isolation between adjacent columns which was intended to force all of them to share currents equally. Unfortunately, simultaneous closure of the columns did not consistently occur. The one column that transferred all the energy catastrophically failed even at modest voltages (2.5 MV).

The primary failure mode was fracturing of the tie rods caused by the axial expansion of the switch column produced by the large gas pressures generated by the arc. Axial expansion of the switch column occurred because of deformation of the assembly end plate located at the pulseline end of the switch. Insulators, usually the ones located at both ends of the column, were also destroyed as the unbroken tie rods would rapidly restore the column to its original length.

Although an occasional failure would be produced by a water arc occurring outside the switch column, most were caused by internal pressures generated in the gas by the passage of large switching currents. The amount of energy deposited in the switch is difficult to measure, but calculations indicate that energies of 30 kJ (peak current of 500 kA) are deposited in the switch in about .5 μsec.[1] These calculations, together with an estimate of an equation of state for the gas, lead to a prediction of 9.5×10^6 Pa (1400psi) for peak switch pressures. Containment of dynamic pressures of this magnitude required a redesign of the original switch hardware. Two different approaches were used to prevent the mechanical failures.

NSWC/WOL tested several plastics to determine which materials were most compatible for switch insulator and tie rod use. Four types of plastics (high molecular weight polyethylene, polypropylene, acrylic, and polycarbonate) were studied for insulator use. Each of the plastics were pressure tested under static and dynamic loading. Both the polyethylene and polypropylene were found to distort sufficiently under pressure to cause o-ring seals to be broken. Furthermore, the polyethylene eroded badly due to surface tracking during electrical tests performed on Casino. The polycarbonate insulators were found to survive static and dynamic pressure tests of up to 7.4×10^7 Pa (1100psi), while the acrylic plastic failed at static pressures as low as 3.4×10^6 Pa (500psi) after cycling.

A glass-reinforced polycarbonate (30% random-oriented glass fiber, 70% polycarbonate resin) was tested, both for strength and electrical properties, as a possible tie rod material. It was found that the glass-filled polycarbonate tie rods exhibited much less elongation and failed at about the same tensile stresses as the pure polycarbonate samples. Pulse testing on Casino revealed no electrical failure when voltages of up to 4.2 MV where impressed across the 46 cm tie rods. NSWC/WOL built a three column switch assembly which used the glass-filled polycarbonate tie rods and 5 cm ID, lexan insulators. The three column assembly was clamped between two 1.3 cm (.5") steel plates that were held by three 5 cm (2") diameter polycarbonate tie bolts to prevent the switches from axially expanding. With this arrangement the switch has been operated at voltages up to 4.2 MV with all energy transferred through one switch column without mechanical failure. During these higher voltages test switch current was sufficient to melt electrode solder joints and electrodes had to be welded to the electric grading fin for support.

PAI built a single column, 10-stage switch that increased the acrylic insulator length, inside diameter, and wall thickness by a factor of two. By increasing the switch colume by a factor of eight the pressures at the insulator wall were greatly reduced. The pure polycarbonate tie rods were also doubled in diameter. This single switch exhibited no mechanical failures during testing of voltage up to 4 MV.

Both designs worked satisfactorily in stopping the failure of the column insulators and tie rods due to the overpressure. The single-column design is more inductive than the six-column switch, but because the insulating surface was moved further from the arc path it is likely to exhibit longer switch life. A single column switch has been used in all subsequent testing.

Discussion of Insulator Electrical Failure

After the switch assembly was designed so that it no longer exhibited mechanical failures, it was discovered that the maximum hold off voltage of the switch degraded with switch use. For a given gas pressure setting the voltage at which the switch would close without command trigger decrease as much as 1.5 MV over a ten-shot firing sequence. Since low jitter, command trigger operation requires the voltage across the switch at the time of trigger arrival to be within about 10% of the self-breakdown voltage, it was not possible to make jitter measurements.

Inspection of the insulator walls showed that faint tracks bridged the length of some of the insulators. Figure 1 indicates location of wall tracks. It was evident that little energy was actually transferred along the insulator wall because of the lack of damage found on either the insulator or the adjacent grading fin. Apparently current passing along the inside wall acts as trigger mechanism for the associated electrodes. Initiation of the main gap closure may occur because of imbalance of the electric field at electrodes due to the surface tracks causing asymetric field distortion. Another possible mechanism is the generation of ultraviolet radiation at the insulator wall that illuminates the electrode.

Attempts to stop the sliding sparks by convoluting the inside insulator wall did not have any measurable effect. The surface contours required that the

sliding sparks, starting at grading fin-insulator-gas triple point, would have to reverse direction against the potential gradient. Furthemore, the convolutions were designed so that blast and ultraviolet radiation from the main gap closure were not directly incident at the triple point. Experiments on Casino showed that the tracking still occurred with tracks passing directly across the convolutions.

Tests of a single stage of a switch at comparable voltages, but much less transferred energy than at Casino, were conducted at PAI. No decrease in the insulator's maximum voltage hold off were observed. These results indicated that insulator breakdown phenomena is energy dependent.

It was hypothesized that the source of the insulator electrical failure was due to one or more of the following: contamination from by-products formed by the electrical breakdown of the sulfur hexafluoride used as the insulating gas[6]; ultraviolet radiation charged[7], causing insulator surface to become charged; micro-fractures of the insulator formed by the dynamic overpressure of the arced insulating gas; insulator surface erosion by hot gases creating a microscopic surface structure that is electrically weaker; or electrode material being plated on the insulator surface. To test these, hypothesis samples of the insulators were sent for surface analyses.* The insulators analyzed included unused plastic, heavily and lightly tracked insulators, and used insulator with no observable insulator tracks.

Scanning Electron Microscopy (SEM) was used to show insulator inner wall topography. Figure 3 shows a comparison of the surface of an unused insulator and one exposed to several switch closures. There is an obvious difference in the contamination level between the two insulators.

Transmission Electron Microscopy (TEM) was used to provide high magnification (up to 50,000x) of the insulators internal structure. A thin section (~1000A thick) TEM micrograph is shown in Figure 4. The micrograph shows copper and zinc deposits (black dots) imbedded in the insulator surface. The size of these particles range from about 250A to 1000A in diameter. No stress cracks were observed in the body of the insulator indicating a lack of obvious structural damage due to blast.

The inside surface of the insulators were analyzed by Energy Dispersive Electron Probe Microanalysis (EDX) to determine the main elemental components several microns into the surface. These tests results showed the presence of copper and zinc on all used insulators, with the tracked insulators exhibiting the largest amounts. The quantity of copper and zinc were found to be approximately equal; a finding that is consistent with the lower energy requirement for the vaporization of zinc and the approximate 2.5 to one concentration superiority of copper in the brass electrodes.

Electron Scan for Chemical Analysis (ESCA) was used to measure the insulator surface properties to a depth of about 20A. The advantage of ESCA is that it not only detects the elements present but also indicates the types of chemical compounds formed. While considerable fluorine was found on the used insulator surfaces, the analysis showed that the oxidation states of the copper and zinc were not due to that element. Also, very little free sulfur was found on the surface of the insulator. These results imply that the breakdown of SF_6 was not likely the cause of the insulator failures.

The brass electrodes were analyzed by Scanning Auger Microscopy (SAM). These tests gave the somewhat suprising result that on the used electrode surface the ratio of copper to zinc was approximately one to one rather than 2.5:1 deeper (~100A) into the metal. The higher zinc concentration is caused by the preferential oxidation of the zinc at the surface.[8] The oxidation of the zinc causes a diffusion gradient which leads to an enhancement of zinc at the surface.

All the surface analyses results point toward deposition of metal electrode particles on the insulators. It cannot be directly proved that the metal particulate is the cause of electrical failure of the insulators. However, the extensive metalization found by the surface analyses will limit switch life and should be suppressed.

Conclusions

Design considerations of gas switches to be used in high voltage, large power systems must take into account the sizable energy that is dissipated in the switch. To reduce the likelihood of mechanical failure the best approach appears to be to increase the volume of the gas which lessens peak pressures to be withstood by the switch components. Consideration of the energy stored in the pressurized gas should be made so that a break of the switch housing does not result in major damage to surrounding equipment.

Surface analyses comparison of used and unused insulators indicate a substantial plating of electrode material on the insulator. Two approaches are suggested for preventing the metal plating on the insulator: first, a change in the electrode material from brass to a tungsten-copper composite may substantially reduce this effect, second, the use of mechanical shields which do not allow a direct line of sight from the arc gap to the insulator. Designs incorporating both of these features are being readied for testing.

References

1. F. J. Sazama and V. L. Kenyon (Proceedings this Conference)

2. M. Kristiansen and M. O. Hagler, "Critical Analysis and Assessment of High Power Switches" T. R. Burke, P.I., Texas Tech University, Lubbock, Tx. Aug 1, 1978.

3. S. Kassel, "Pulsed-Power Research and Development in the USSR," RAND/R-2212-ARPA, RAND, Santa Monica, CA. 90406, May 1978.

*Structure Probe, Inc.
230 Forrest Street. Metuchen. NS 08840

4. D. Conte, Naval Research Laboratory (Private Communication).

5. "Test Report, DQ Switch Tests at Gamble II," PAR 75-1, Pulsar Associates, Inc. Sep 19, 1975.

6. A. A. Hudson, "Degradation of SF_6 in Electrical Equipment: Toxic and Corrosive Effects - A Resume' of Published Information," ERA REP(G.B.) 5815 1967.

7. W. Crewson, Pulsar Associates, Inc. (Private Communication)

8. J. S. Duerr, Structure Probe, Inc. (Private Communication)

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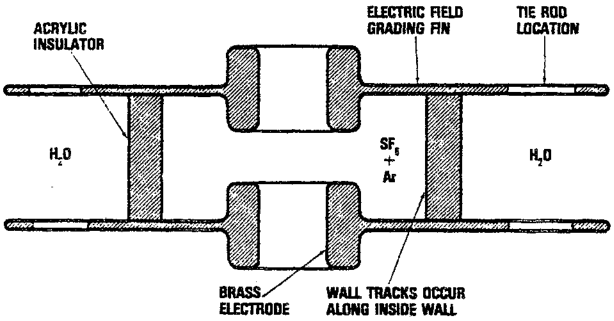

Fig. 1. Cross-sectional view of single section of multistage gas switch.

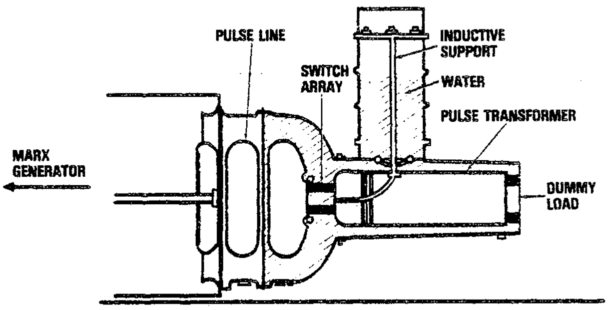

Fig. 2. Experimental arrangement used for testing gas switches on the Casino simulator.

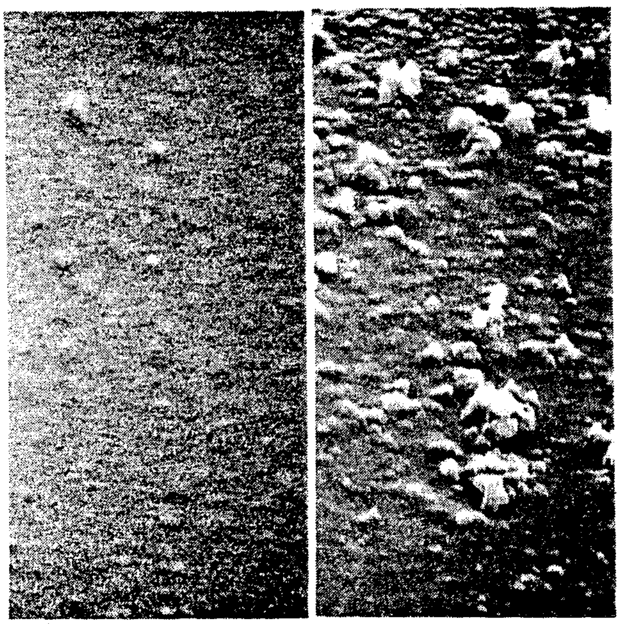

Fig. 3. SEM micrographs (10,000X) comparing surface contamination of unused plastic (left photo) with insulator exposed to ten switch closures.

Fig. 4. TEM micrograph (50,000X) cross-sectional view of insulator exposed to ten switch closures. Black dots along the insulator surface are copper and zinc particles which originate from the brass electrodes .Insulator structure lies to right of meta particles.